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NO DIFFUSE H_2 IN THE METAL-DEFICIENT GALAXY I Zw 18

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ABSTRACT

The metal-deficient starburst galaxy I Zw 18 has been observed with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) in a search for H_2 molecules. The spectrum obtained with an aperture covering the full galaxy shows no absorption lines of diffuse H_2 at the radial velocity of the galaxy. The upper limit for the diffuse H_2 column density is found to be very low, $N(H_2) \lesssim 10^{15}$ cm^{-2} (10 σ), unlike our Galaxy where H_2 is generally present for even low H I column densities. Although the H I column density here is as high as $N(\mathrm{H\ I}) \approx 2 \times 10^{21}$ cm^{-2}, we observe $2N(H_2)/N(\mathrm{H\ I}) \ll 10^{-6}$. We cannot exclude the possibility that some H_2 could be in very dense, small, and discrete clumps that cannot be detected with the present observation. However, the remarkable absence of diffuse H_2 in this metal-poor galaxy can be explained by the low abundance of dust grains (needed to form this molecule from H atoms), the high ultraviolet flux, and the low density of the H I cloud surrounding the star-forming regions. Thus, having eliminated diffuse H_2 as a significant contributor to the total mass, it appears that the gas of the galaxy is dominated by H I and that the high dynamical mass is not composed of cold and diffuse baryonic dark matter.

Subject headings: galaxies: abundances — galaxies: dwarf — galaxies: individual (I Zw 18) — galaxies: ISM — ISM: molecules — ultraviolet: galaxies

1. INTRODUCTION

I Zw 18 (Mrk 116) is a dwarf blue compact galaxy presently experiencing a strong burst of star formation that has produced a pair of bright H II regions. This galaxy has the smallest known abundance of heavy elements that are derived from the ionized gaseous component. Its oxygen abundance is only ~1/50 of that of the Sun. The distribution and kinematics of neutral hydrogen derived from aperture-synthesis observations have been discussed in several works. These works have derived H I masses in the range of (3–7) × 10^7 $M_\odot$ and dynamical masses in the range of (3–9) × 10^8 $M_\odot$ (Lequeux & Viallefond 1980; Viallefond, Lequeux, & Comte 1987; van Zee, Westphal, & Haynes 1998). Van Zee et al. (1998) have emphasized the complexity of the H I velocity fields, while Martin (1996) and Petrosian et al. (1997) have discussed the ionized component. It has been suggested that objects with a localized massive star formation surrounded by large H I envelopes might contain a significant reservoir of molecular hydrogen. Such material could represent a significant fraction of the dark matter (Lequeux & Viallefond 1980). Attempts to detect CO in H II galaxies have so far been unsuccessful (Combes 1986; Young et al. 1986; Arnault et al. 1988; Sage et al. 1992; Israël, Tacconi, & Baas 1995; Gondhalekar et al. 1998). This lack of detection does not necessarily imply a lack of H_2; the CO excitation could be lower than for molecular clouds in our Galaxy, or CO might be more photo-dissociated than H_2, but perhaps most importantly, C and O are highly underabundant in these metal-deficient galaxies. The lack of detectable molecular material also has other important implications for galaxies like I Zw 18. Given the chemically unevolved nature of I Zw 18 and its lack of organized gas dynamics and/or spiral arms, it is unclear where and how this galaxy formed the molecular gas thought to be required to form the current generation of young stars.

Therefore, we observed I Zw 18 with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*; Moos et al. 2000) with the aim of detecting cold molecular hydrogen lines in absorption against the stellar continuum of blue massive stellar clusters. In § 2 we describe the observations and the data analysis; the results are discussed in § 3.

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2. DATA ANALYSIS

I Zw 18 has been observed for 31,600 s on 1999 November 28 with *FUSE* through the two LiF channels (~ 980–1187 Å). The large entrance aperture (30″ × 30″) has been used, fully covering the galaxy. The data have been processed with the pipeline version 1.5. The spectral resolution is defined by both the instrument and the size of the galaxy (10″). We find a resolution of about $\lambda/\Delta\lambda \sim 10{,}000$ with a signal-to-noise ratio (S/N) of ~10 per resolution element.

Many absorption lines are clearly detected. They correspond to the three main components at different radial velocities: −260, −100, and 650 km s^{-1}. These can easily be identified with the known high-velocity cloud at −160 km s^{-1}, the clouds within the Galaxy expected at low radial velocity, and I Zw 18 itself with a redshift of 750 km s^{-1}. We thus conclude that there is a systematic wavelength shift in the whole spectrum corresponding to a blueshift of about 100 km s^{-1}, respectively. This systematic wavelength shift can be explained by the preliminary wavelength calibration of *FUSE* and by the position of the target possibly off-center of the slit. All the velocities quoted below refer to the

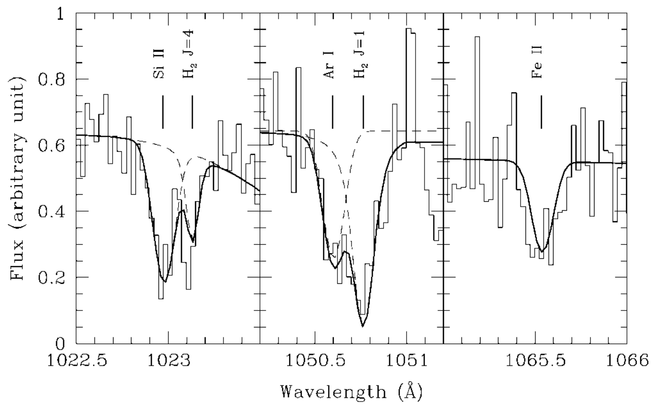

FIG. 1.—Plot of some atomic lines detected at ∼750 km s^{-1}. The absorption lines of Si II, Ar I, and Fe II are from I Zw 18. The Si II and Ar I lines are blended with Galactic H_2 lines. This blend is easily resolved because the Galactic H_2 is detected in many other lines.

observed velocities corrected by this systematic effect assumed to be exactly 100 km s^{-1}.

The high-velocity cloud at −160 km s^{-1} is detected in C II, Cr II, Fe II, and Si II lines. The second component identified with Galactic clouds shows absorption lines not only from atoms and ions (e.g., C II, O I, Fe II, and Si II) but also from molecular hydrogen. Lines from H_2 at levels of up to at least $J = 5$ are detected. This is the only component showing the presence of these electronic transitions of H_2. This component shows a complex structure, suggesting the presence of several interstellar clouds separated by up to 20 km s^{-1}, and will not be detailed further. Finally, the third component, detected at 750 km s^{-1}, is seen in Ar I, N I, Fe II, and Si II lines (Fig. 1).

In addition to these three main components, a complex structure is observed around 1032 and 1037 Å. This corresponds to the presence of O VI lines with radial velocities between −100 and +150 km s^{-1} originating in the Galactic halo.

No line from H_2 is observed at the radial velocity of I Zw 18 (Fig. 2). We calculated the upper limits of the H_2 column densities assuming an intrinsic width of the lines of $b = 18$ km s^{-1} (van Zee et al. 1998). The limits have been estimated by calculating the difference between a simulated spectrum and the observed spectrum in nine Lyman bands (0–0 to 8–0) and by calculating the corresponding increase of the χ^2 of the fit to the spectrum. The upper limits quoted in Table 1 give an increase of the χ^2 larger than 100, corresponding to a nondetection at the ∼10 σ level. These limits are thus very conservative and correspond to a total column density of $N_{\rm tot}(H_2) \lesssim 10^{15}$ cm^{-2}. A different intrinsic width of the lines would not change the result significantly.

The H I Lyβ line is strongly perturbed by the airglow lines. However, using only the blue wing of the absorption line and assuming that this wing is due to the H I of I Zw 18 at 750 km s^{-1}, it is possible to obtain an estimate of the H I column density. We find N(H I) ≈ 2.1 × 10^{21} cm^{-2}. This value is consistent with N(H I) ≈ 3.5 × 10^{21} cm^{-2} obtained with the *Hubble Space Telescope* (*HST*) with a narrow slit (Kunth et al. 1994) and the peak column density of 3.0 × 10^{21} cm^{-2} obtained with observations of the 21 cm emission line. Assuming a constant $N(H_2)/N$(H I) ratio across the whole galaxy, we can scale the upper limit on the H_2 column density to a limit for the total mass of diffuse H_2, yielding $M_{H_2} \lesssim 30\ M_\odot$.

Other lines of atoms and ions are observed in the I Zw 18 system at 750 km s^{-1}. For instance, lines of Ar I, N I, Fe II, and Si II are clearly detected. Neither O VI nor the electronic

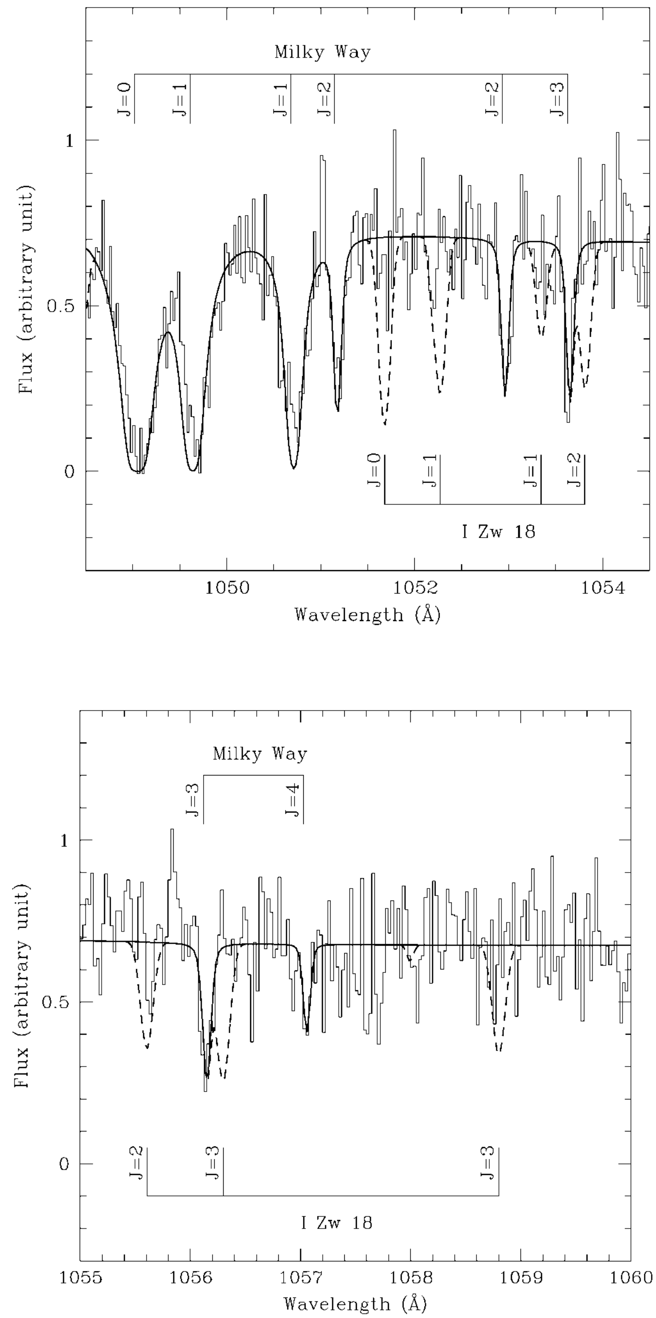

FIG. 2.—Plot of the 4–0 H_2 Lyman bands. Although the Galactic H I column density (∼10^{20} cm^{-2}) is lower than the one from I Zw 18 (∼10^{21} cm^{-2}), the Galactic H_2 is easily detected (∼10^{20} cm^{-2}). No line of the H_2 bands is detected at the radial velocity of I Zw 18. The dashed lines show the expected lines if the column density of H_2 had been 10^{15} cm^{-2} in the plotted J-levels.

TABLE 1

UPPER LIMITS ON THE H_2 CONTENT OF I Zw 18 AT AN ∼10 σ LEVEL

Molecule	J	N (cm^{-2})
H_2	0	<5 × 10^{14}
	1	<6 × 10^{14}
	2	<5 × 10^{14}
	3	<5 × 10^{14}
	4	<9 × 10^{14}

transitions of CO are detected at the I Zw 18 radial velocity. The lack of CO absorption lines is not surprising since, contrary to diffuse H_2, CO should be confined in very dense clouds that are opaque to UV sources. The problem of O VI will be discussed in a forthcoming paper.

3. DISCUSSION

The interpretation of the lack of absorption lines of H_2 in the spectrum of I Zw 18 deserves a detailed discussion. Note first that *FUSE* gives access to the average absorption over the full body of I Zw 18, providing $\gtrsim 10^3$ lines of sight to stars emitting in the far-UV and gathered in a central region approximately 10″ wide. Some of these stars are resolved by the *HST* (Dufour et al. 1996). Our observations are not sensitive to dense molecular clouds since (1) dust, even in minute amounts, will hide the background stars in the far-UV and (2) even if such clouds were transparent to UV photons, H_2 absorption lines would not be detected at our S/N unless the covering fraction is larger than ∼10%. On the other hand, our observations are very sensitive to diffuse H_2. Its absence is very unusual. Indeed, in our Galaxy H_2 is strongly detected for H I column densities larger than a few 10^{20} cm^{-2} and is often detected for lower N(H I) (Dixon, Hurwitz, & Bowyer 1998). With $2N(H_2)/N(\mathrm{H\,I}) \ll 10^{-6}$ and an H I column density as high as N(H I) $\approx 2 \times 10^{21}$ cm^{-2}, our observation is placed in the extreme bottom right corner of Figure 5 of Dixon et al. (1998), representing the fraction of molecular hydrogen versus N(H I). Such an extreme situation has never been observed within a galaxy. Even the Magellanic Clouds, with subsolar metallicities and high far-UV radiation fields, show detectable H_2 along sight lines with lower H I column densities (e.g., Friedman et al. 2000; Shull et al. 2000). We also would like to stress that this result raises an interesting similarity to what is observed in the damped Lyα systems in QSO lines of sight at higher redshift. Despite their high levels of H I, having low metalicity, low dust content, and a high-UV environment, they also present no detectable H_2 (Black, Chafee, & Foltz 1987).

We now show that the lack of H_2 in the diffuse interstellar medium of I Zw 18 is a consequence of the low abundance of grains, of the high ultraviolet flux, and of the low atomic density in the H I cloud surrounding I Zw 18.

There are two possible mechanisms for the formation of H_2 in the H I cloud: formation via H^- (see, e.g., Jenkins & Peimbert 1997) or the combination of two H atoms on a dust grain (Hollenbach & Salpeter 1971). A third mechanism involving the production of H_2^+ by the radiative association of H and H^+ is very inefficient in the present case since the reaction is slow and will not be considered further. The first mechanism for H_2 formation starts with the formation of a negative ion, $H + e \rightarrow H^- + h\nu$, with a rate of $1.0 \times 10^{-15} T_3 \exp(-T_3/7)$ cm^3 s^{-1}, T_3 being the temperature in units of 10^3 K (Jenkins & Peimbert 1997). This is followed by the faster associative detachment reaction $H^- + H \rightarrow H_2 + e$. The electrons come mainly from the photoionization of carbon, n_e = (C/H)n(H). We assume that the abundance of carbon in the H I cloud is the same as in the H II region, C/H = 3.5×10^{-6} (Garnett et al. 1997). The rate of formation is then as low as $\sim 10^{-20} n(\mathrm{H})^2$ cm^3 s^{-1} at a temperature of 10^4 K, the most favorable case, so that the mechanism very inefficient unless the medium contains clumps with very high densities.

The formation of H_2 on grains is a more efficient mechanism if the dust is cold enough for the H atoms to stick and remain on the grain surface long enough to combine. To estimate the grain temperature, we examine what happens at the edge of the H I cloud of I Zw 18, where the UV flux that photodissociates H_2 is minimal. The angular radius of the H I cloud is approximately 30″ from the VLA map of van Zee et al. (1998), corresponding to a radius R_0 = 1.7 kpc at the distance of I Zw 18 and taken as 11.5 Mpc from its radial velocity of 750 km s^{-1} (H_0 = 65 km s^{-1} Mpc^{-1}). The radiation flux from the ionizing stars of I Zw 18 around 1000 Å measured by *FUSE* or extrapolated from *IUE* observations is about 3×10^{-14} ergs s^{-1} cm^{-2} Å^{-1}. Correcting for the Galactic extinction [$E(B-V)$ = 0.04 mag; Kunth et al. 1994], we obtain a UV flux at the Earth of approximately 4.5×10^{-14} ergs s^{-1} cm^{-2} Å^{-1}. This yields at R_0 a flux of $F_{1000} \simeq 2 \times 10^{-6}$ ergs s^{-1} cm^{-2} Å^{-1}. We finally find the grain temperature at R_0 by solving the temperature equilibrium equation $\pi a^2 \int Q_a(\lambda) F_\lambda \, d\lambda = 4\pi a^2 \int Q_a(\lambda) \pi B_\lambda(T) d\lambda$, where a is the radius of the grain assumed to be spherical, $Q_a(\lambda)$ is its absorption efficiency, F_λ is the incoming UV flux, and $B_\lambda(T)$ is the Planck function at the temperature T of the grain. As any kind of grain is strongly absorbing in the far-UV that strongly dominates the radiation field, we take $Q_a \simeq 1$ in the left side of the equation. In the far-IR where the grains emit, we take $Q_a(\lambda) \simeq 0.1(\lambda/100\ \mu\mathrm{m})^{-2}(a/0.1\ \mu\mathrm{m})$ (Draine & Lee 1984). It is then possible to solve the temperature equation analytically, finding that at R_0, $T \simeq 15.5(a/0.1\ \mu\mathrm{m})^{-1/6}$ K. This grain temperature is close to that in the diffuse Galactic interstellar medium and allows the formation of H_2. However, T increases as $R^{-1/3}$ closer to I Zw 18, and H_2 cannot form on grains in the inner parts of the H I cloud.

In the steady state, the molecular hydrogen is also destroyed through absorption in the Lyman bands, and the resulting H_2 column density can be estimated. We can take for the formation rate on grains $\mathcal{R}$ the canonical Galactic value of $10^{-17} n(\mathrm{H})^2$ cm^3 s^{-1} (Hollenbach & Salpeter 1971) divided by 50 since the dust-to-gas ratio is less than 1/50 of the Galactic value (Kunth et al. 1994). In the present case, where the H_2 electronic bands are optically thin, the fraction of molecular hydrogen $f(H_2)$ = $2n(H_2)/[2n(H_2) + n(\mathrm{H})]$ is (Jura 1974)

$$f(H_2) = 2\mathcal{R} n(\mathrm{H})/I, \quad (1)$$

where I is a photodissociation rate. Jura (1974) has calculated I for different cases, and we simply use his estimate close to the O9.5 V star ζ Oph, scaled with F_{1000}, the flux at 1000 Å at the radius R_0 of I Zw 18. We will assume that the cloud is spherical and uniform, in which case its density is n(H) = $N(\mathrm{H\,I})/R_0$ = 0.4 atoms cm^{-3}, N(H I) being the column density we measure in front of I Zw 18. We obtain $f(H_2) \simeq 2 \times 10^{-9}$. The abundance of H_2 is still smaller closer to I Zw 18 since the UV flux is accordingly larger. Thus, the calculated column density of H_2 is

$$N(H_2) \lesssim 1 \times 10^{-9} N(\mathrm{H\,I}) \approx 2 \times 10^{12} \text{ molecules cm}^{-2}, \quad (2)$$

which is less than the observed upper limit by more than 2 orders of magnitude.

We thus conclude that our observation shows that the diffuse interstellar matter surrounding I Zw 18 cannot be very inhomogeneous at large scales, otherwise H_2 would have been observed. However, it cannot be excluded that this medium contains molecular clouds and in particular the kind of very dense, discrete molecular clumps proposed by Pfenniger, Combes, & Martinet (1994) to account for the dark matter in our Galaxy. These clumps would escape detection since the associated absorption would be observed only in front of stars that, although

very numerous, have a very small total surface coverage. However, the suggestion of Lequeux & Viallefond (1980) that the dark matter seen dynamically in I Zw 18 is made of widespread diffuse molecular hydrogen is no longer tenable after the present observations.

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